

## **The Effects of Sediment Properties on Low Frequency Acoustic Propagation**

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### **LONG-TERM GOALS**

Our work focuses on understanding the frequency and depth dependence of compressional wave attenuation and developing new inversion schemes for shear wave properties. Our initial investigations have indicated that water-borne acoustic arrival properties such as their Airy Phase are sensitive to sediment shear properties. Our major emphasis this year has been to develop and test inversion schemes for simultaneous estimation of compressional and shear properties.

The long term goals of our research are to:

- Improve inversion schemes for the estimation of sediment geoacoustic properties using low frequency broadband acoustic signals at short and long ranges.
- Continue fine-tuning our Shear Measurement System, recently developed under a DURIP grant, for short range interface/Scholte wave-based inversions for shear properties.
- Adapt our long range sediment tomography technique for compressional and shear wave speeds, and attenuation profiles utilizing the broadband Combustive Sound Source (CSS) developed at the Applied Research Laboratories (ARL), University of Texas.

### **OBJECTIVES**

We are pursuing the long term goals listed above by executing the objectives listed below.

**A. Engineering tests:** A shear measurement system has been developed and tested at URI as part of a DURIP grant. Additional sensors are being integrated into this system and further engineering tests (on land and at sea) have been conducted to make the system ready for deployment during future ONR field tests.

**B. Signal processing:** We continue to explore new signal processing techniques in order to extract the arrival times in our long range sediment tomography technique. The accomplishments associated with this objective can be summarized as follows:

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- a. Adapted new signal processing algorithm (warping transform (Bonnell and Chapman, 2011) and  $k$ - $\omega$  transform of the Vertical Line Array data) for time-frequency analyses for more accurate extraction of modal arrival times and frequencies especially near Airy frequencies.
- b. Continued the development of techniques for identifying surface wave arrivals on both the vertical axis and 3-axis geophones.

**C. Modeling:** Development of a forward model which can incorporate elastic properties and account for the natural layering in the sediments is an important objective of our study. In addition we are also undertaking studies on the effect of ocean acidification on acoustic propagation and mode conversion in range dependent environments. The topics of research can be summarized as follows:

- a. Extend the investigation into shear effects using layered bottoms using models based on dynamic stiffness methods. Finite element modeling also will be explored in collaboration with ARL-UT (Marcia Isakson).
- b. Develop an inversion scheme to estimate shear profile using a suitable model identified in task (a).
- c. Understanding the effect of ocean acidification on acoustic propagation. The PIs (Miller and Potty) are trying to get funding from the state agencies to investigate this problem through a field study in Narragansett Bay. The collaborators in this proposed study are Andrea Simmons and Laura Kloepper (Brown University).
- d. Developing mathematical methods for modeling mode conversions in range-dependent environments. This work is carried out by Charles White as part of his PhD dissertation research.

**D. Measurements and inversions:** One of the major objectives of the study is to design and implement inversion schemes to estimate sediment geoacoustic properties. The tasks associated with this objective are summarized as follows:

- a. Develop inversion schemes for compressional and shear profiles using Scholte wave data.
- b. Deploy the Shear Measurement System in field experiments in preparation for the ONR seabed characterization experiment in the Gulf of Mexico.

## **E. Experiment design**

We also propose a task to assist ONR and other PIs in designing a new shallow water experiment. A site has been identified in the New England Mud Patch which is close to the Shelfbreak Primer Experimental site. The PIs will participate in the planning workshops and contribute to the science objectives of the seabed interaction experiment.

## **APPROACH**

A shear measurement system consisting of geophone/hydrophone array and WHOI-SHRU data acquisition system was designed and developed as part of a DURIP grant. Data were collected during three field tests so far which are being used to develop a scheme to estimate shear properties. Efficient inversion approaches are being developed for this purpose. Application of recent signal processing techniques is being pursued for improving the time-frequency analysis of the broadband data for better mode identification and extraction of modal arrival data for long range inversions.

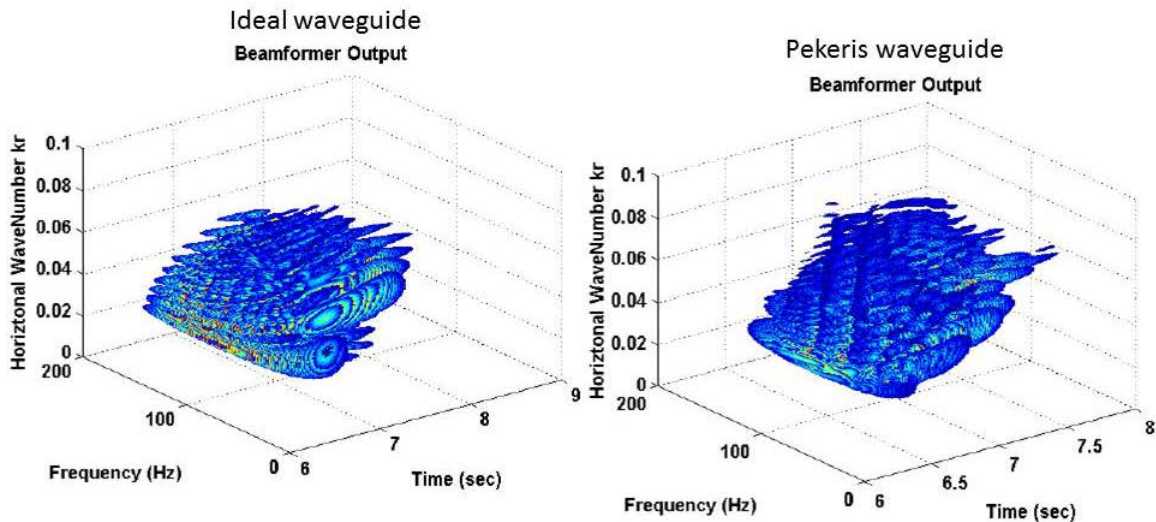
## WORK COMPLETED

Former graduate student, Jennifer Giard, designed and performed a field test in Davisville Basin in Narragansett Bay, RI as part of her Master's thesis study. Estimation of shear properties of the bottom using Scholte wave data is also being pursued currently. Graduate student George Dossot has completed his Ph. D dissertation and is currently preparing manuscripts based on this work for publication. Current Ph. D student Charles White is focusing on the mode conversion effects in range dependent environments. Some of the results from these investigations are highlighted below. The PIs are preparing for the upcoming Seabed Experiment planning meeting to be held in ARL-UT Austin during 9-11, December, 2014.

## RESULTS

Some of the results of work completed during last year are summarized in the following sections.

### A. Time-frequency analysis techniques



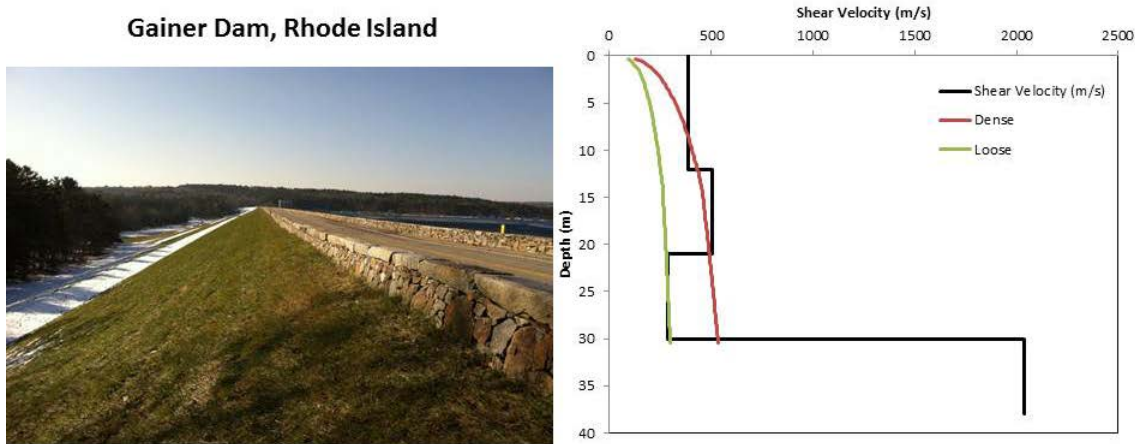
***Figure 1. The  $k$ - $\omega$  spectrogram for an ideal waveguide (left panel) and Pekeris waveguide (right panel). The VLA data were simulated using a normal mode code.***

A new technique to extract modal arrival time using vertical array data was developed. This is based on beam forming in horizontal wavenumber ( $k_r$ ) at each instant in time so that you end up with  $k$ - $\omega$  diagram that evolves with time: a “ $k$ - $\omega$  spectrogram.” Such a  $k$ - $\omega$  spectrogram would have an extra dimension to help separate the modes from one another, making it easier to extract the arrival times of the modes. For a given time and horizontal wavenumber the arrival time is unique. This allows the creation of the 3D plots that can be used to separate out the arrival times (Figure 1). The left panel in Figure 1 corresponds to simulated data for an ideal waveguide. The right panel corresponds to data from a Pekeris type waveguide.

## B. Shear Measurement System based on interface wave dispersion:

**a. Shallow water test in Davisville, RI:** We have acquired a geophone/hydrophone array under a DURIP grant (*Seafloor Shear Measurement Using Interface Waves*, Miller and Potty PIs) capable of collecting interface wave data. A test of URI's Shear Measurement System was completed on February 5, 2013 in the Davisville Basin in Rhode Island using a 114 kg weight impacting the bottom. The inversion scheme employed to invert the dispersion curve data into shear speed profiles provided results consistent with the range of shear speed values estimated from the boring logs at the Davisville site. The analysis of this data is ongoing and we are collaborating with Isakson (ARL-UT) in the FEM modeling in this effort.

**b. Test on land – Gainer Dam, RI:** The shear measurement system was deployed as part of a project which focused on the preliminary evaluation of the seismic performance of the Gainer Memorial dam in RI. The Rayleigh surface waves were measured using the geophone array. The surface waves were excited by dropping a weight. The shear wave velocities were calculated from the Rayleigh surface wave velocities. The dynamic stiffness matrix approach was modified to calculate the Rayleigh wave phase velocities with sediment parameters as inputs. The shear wave velocity obtained from the inversions compares well with predictions for loose and dense soils. It also clearly captures the loose layer of soil at a depth of approximately 21 meters (Figure 2) that corresponds to the soils composing the core trench (very loose sediment).



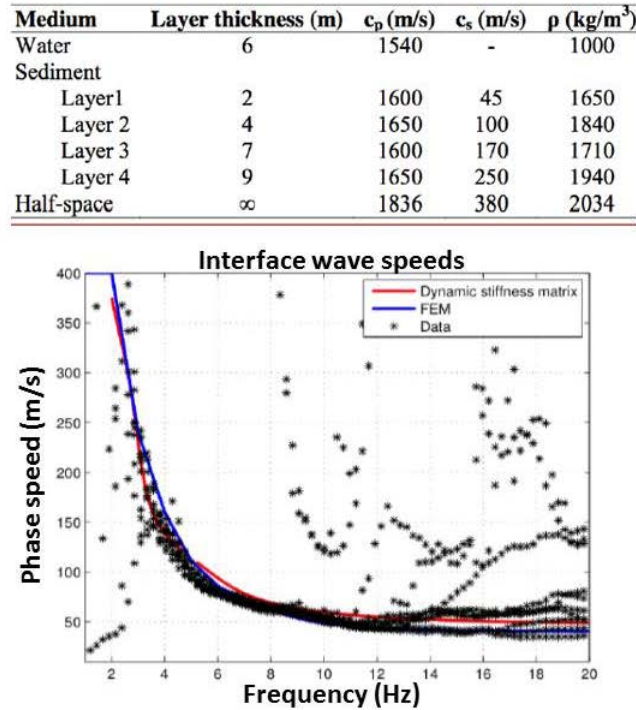
**Figure 2: Shear wave velocity profile of Gainer Dam compared to predictions for loose and dense soils.**

## D. Modeling

Efforts are underway to develop better modeling tools to understand the wave propagation physics and for incorporation into inversion schemes. This work is summarized here.

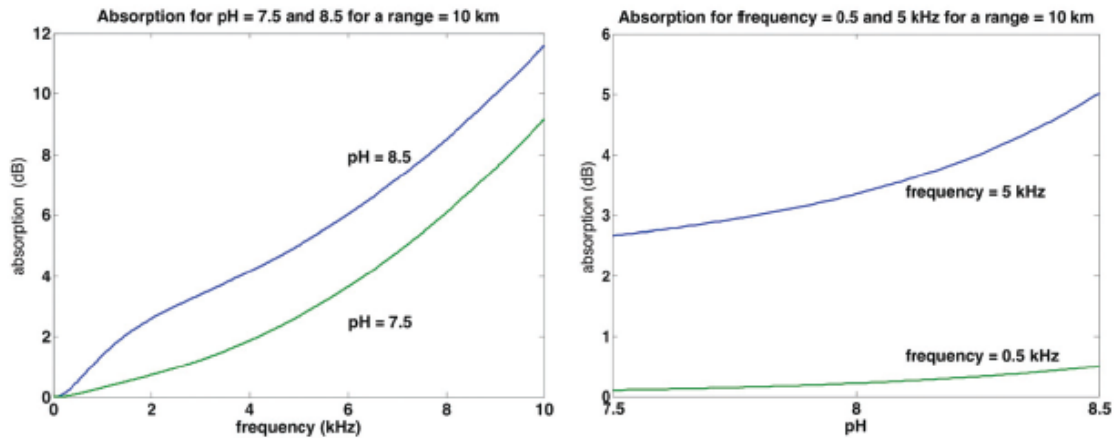
**a. Dynamic stiffness matrix approach:** In the new model based on the dynamic stiffness matrix approach, the dispersion relationship for the Scholte wave has been computed from the global stiffness matrix  $K_{\text{total}}$  of the water over layered bottom system. The model was validated by comparing the output of the model with results from Rauch (1980) for a shallow water waveguide with layered

bottom. Data collected from a field test in Narragansett Bay was used to invert for the shear wave speed in the sediment layers. The sediment properties shown in the table (top panel, Figure 3) are taken from the inversion and previously published core analysis. The data were then compared to predicted dispersion values as shown in the bottom panel of Figure 3. The red curve is from the Dynamic Stiffness Matrix model and the blue curve is from the FEM model (Goldsberry and Isakson, 2013). The agreement between the two models and the data is very good.



*Figure 3. Comparison of the dynamic stiffness model with Finite Element Modeling results (Goldsberry and Isakson, 2013). The bottom model used in the model consists of four layers of sediment above the half-space. The properties of the sediment used in the model calculation are shown in the top panel.*

**b. Effect of Ocean Acidification on Acoustic Propagation:** One of the consequences of increasing atmospheric CO<sub>2</sub> is ocean acidification. The reduction in pH is a direct result of increased CO<sub>2</sub> dissolved in seawater. Figure 4 illustrates the dependence of sound absorption on frequency and pH. The left panel shows how the absorption (in dB) between a pH of 7.5 and 8.5 changes nonlinearly across 500 Hz to 10 kHz. The right panel shows how the absorption between a frequency of 0.5 and 5 kHz changes nonlinearly across a pH range from 7.5 to 8.5. These predicted changes in sound absorption have yet to be empirically tested in the ocean because logistics have prevented scientists from acidifying the large volumes of seawater necessary to observe decreases in absorption. Fortunately, the environment of Rhode Island provides a unique natural laboratory for such an investigation. Existing data (from two stations from the Narragansett Bay Fixed-Site Water Quality Monitoring Network, NBSFMN) indicate that, during the summer, pH at both of these sites has a range of approximately 1 pH unit (Figure 5). This pH range in the Bay encompasses the pH decrease that is projected over the next 100 years. This characteristic of Narragansett Bay provides a natural laboratory to conduct the first experimental test of the hypothesis that a reduction in pH will result in decreased low frequency sound absorption, leading to wider spread of low frequency sounds.

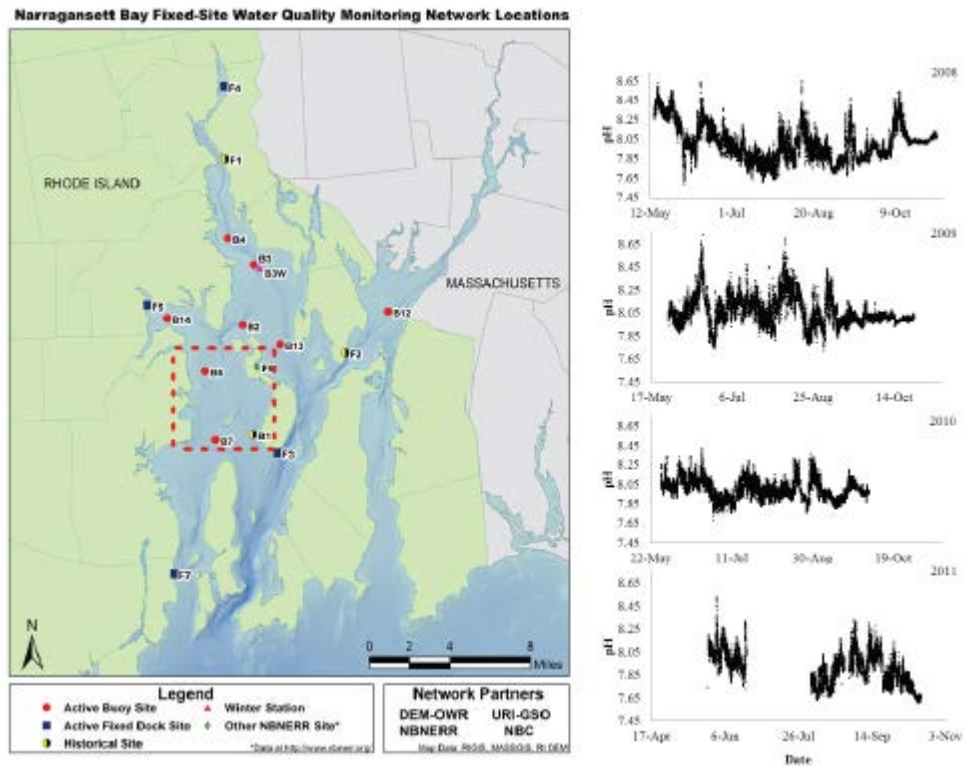


**Figure 4:** Left panel shows the absorption (in dB) at 10 km for pH values 7.5 and 8.5 as a function of frequency. The right panel shows the absorption (in dB) at 10 km at two frequencies 0.5 and 5 kHz for pH values 7.5 and 8.5.

### E. High Resolution Profiling of Ground Properties using Rayleigh Wave Dispersion

This project was funded by US Army Research Laboratory (Greg Fischer, POC). Our goal is to demonstrate the utility of Rayleigh wave dispersion for estimating the properties of the top 1 to 2 m of soil and/or pavement. We propose to perform a demonstration project involving both active and passive sensing using the dispersion of high frequency Rayleigh waves (100-500 Hz) to estimate the properties of the top 1 to 2 m of soil and/or pavement. A number of accelerometers will be used to measure the Rayleigh waves. This project has just started and the sensor system is being acquired and assembled. We anticipate that this study will provide valuable insight into the use of our surface wave method for high resolution estimates of the shear speed near surface. We plan to test this approach on land as part of this project and explore possibility of applying this technique in shallow water in future. Graduate student Chris Norton is working on this project.





**Figure 5: Left: Data from a seasonal monitoring station near the proposed experiment site, known as West Passage (MV-B6). Right: Fluctuation in pH values over time. The data were obtained from the NBFSMN data repository.**

## F. Glider Acoustic Sensing of Sediments (GLASS) Project

The Glider Acoustic Sensing of Sediments (GLASS) experiment was held 10 km off the coast of Italy in July and August 2012. The participating organizations were the Centre for Maritime Research and Experimentation (CMRE), Portland State University, Naval Undersea Warfare Center, and the University of Rhode Island. The Chief Scientist was James H. Miller (CMRE/URI) and the Principle Investigator was Peter Nielsen from CMRE. ONR Global and CMRE provided funding for the project. The goals of this experiment were to 1) Test the potential for a passive fathometer sensing of sediment structure using local ambient noise measured on a short vertical array, 2) evaluate adaptive beamforming algorithms using a tetrahedral array, (Gebbie et. al., 2013, Gebbie et. al., 2014) and 3) assess the potential for single channel inversion of sediment properties using ship generated noise. (Crocker et al., 2014)

## IMPACT/APPLICATIONS

The inversion scheme using explosive sources is suitable for rapid estimation of acoustic properties of sediments in shallow water. This method is cost effective as a single sonobuoy and air-deployed explosives can provide the data. Using multiple sources and receivers sediment properties would allow an area to be mapped. Scholte wave based methods are ideal for the estimation of shear speed in the bottom.





***Figure 6. Upper Panel: Location of the Glider Acoustic Sensing of Sediments (GLASS) experiment off the coast of Italy. Lower Panel: The Folaga glider equipped with the GLASS hydrophone array on the bow.***

## TRANSITIONS

The sediment parameters obtained by this inversion will compliment the forward modeling efforts. The sediment tomography technique is suitable for forward force deployment when rapid assessment of environmental characteristics is necessary. In addition to naval air ASW applications using sonobuoys and SUS charges, this technique would be compatible with Navy special operations involving autonomous vehicles.

## RELATED PROJECTS

None

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## HONORS/AWARDS/PRIZES

**James Miller** served as President of the Acoustical Society of America in 2013-2014.

**Gopu Potty** is serving as one of the Associated Editors for IEEE Journal of Oceanic Engineering since July, 2011.

**James Miller and Gopu Potty** were co-chairs of the Acoustical Society of America Providence, RI meeting held in 2014.

**Gopu Potty** was elected Fellow of the Acoustical Society of America "*for contributions to ocean acoustic inversion methods in shallow water.*"

**Gopu Potty** was nominated as the Acoustical Oceanography representative to the ASA Committee on Standards (ASACOS)

**Gopu Potty** is serving on the International Advisory Committee and Technical Committee of the 2011 International Symposium on Ocean Electronics, India, 16-18, October 23-25, 2013.